Validation of Satellite-Deduced Vertical Profile of Cloud Droplet Effective Radius Using ARM Ground-Based Radar Measurements

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Introduction

Clouds play an important role in governing the earth's radiation budget and climate. Even small changes in their abundance and distribution can alter the climate more effectively than anticipated changes in anthropogenic aerosols and trace gases that affect global change. However, there is a dearth of observations concerning the vertical structure of cloud microphysics. Droplet Effective Radius (DER) is one of the most important cloud microphysical parameters that influences the earth's climate through its effects on radiative transfer, hydrological cycle, and cloud and climate feedbacks, but there is a gap in knowledge concerning cloud DER vertical variation in climate studies. Since cloud radiative properties are remarkably sensitive to changes in cloud microphysical properties, e.g., cloud DER and water content; it is pivotal to have routine satellite observations to gain systematic knowledge on the vertical variability of cloud DER, both at local and global scales.

Many earlier studies on the retrieval of cloud DER from satellite observations have been devoted to the spectral measurement at the nominal 3.7-µm wavelength of the National Oceanic and Atmospheric Administration (NOAA) advanced very high resolution radiometer (AVHRR) (Arking and Childs 1985; Coakley et al. 1987; Han et al. 1994; Platnick and Twomey 1994; Nakajima and Nakajima 1995). However, such retrieval is only susceptible to the DER at near the cloud top due to strong absorption by cloud droplets at this wavelength. Such 3.7-µm retrieval is only valid for clouds having homogeneous DER vertical variations. For inhomogeneous DER vertical variations, this retrieval may only represent a shallow layer at near cloud top and not the bulk property of the cloud column.

Now, the National Aeronautics and Space Administration (NASA) moderate resolution imaging spectroradiometer (MODIS) of the NASA earth observing system (EOS) (King et al. 1992) provides routine satellite observations at multiple near-infrared (NIR) wavelengths at 1.65, 2.15, and 3.75 μm. These NIR measurements possess characteristics of different photon penetration depths within the cloud because absorption by cloud droplets differs appreciably among the three wavelengths. The DER information carried by the multi-spectral measurements has the potential to infer the trend of DER vertical variations in a cloud column. Chang and Li (2002) presented a theoretical study on the potential of using multi-spectral NIR measurements for estimating the vertical variations of cloud DER, which can be representative by a linear DER vertical profile. Since cloud formed by adiabatic or pseudo-adiabatic cooling often displays a trend of near-linear increase in DER with height, an assumption of a linear DER profile should be valid for inferring the DER vertical variability. Among such category of clouds are a large number of low-level, non-precipitating, stratus and stratocumulus clouds observed in many experiments, where an increase in liquid water content (LWC) with height was mainly driven by an increase in droplet size (Miles et al. 2000).

In light of such a linear DER vertical variation, this study examines the performance of the retrieval of an optimum linear DER profile by using the MODIS multi-spectral satellite observations overpass at the Southern Great Plains (SGP) Oklahoma Central Facility (CF) site of the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program (Stokes and Schwartz 1994). The retrieved linear DER profiles are compared with those retrieved from the ground-based radar reflectivity measurements at the ARM SGP using two retrieval algorithms proposed by Frisch et al. (1995) and Dong and Mace (2002). The linear DER retrievals are also compared with the conventional DER retrievals based on a single 3.7-μm measurement.

Radiative Transfer Model

The linear DER retrieval method employs the lookup-table technique by comparing the MODIS observations with radiative-transfer-model calculations. Large sets of reflectance lookup tables were calculated for the MODIS 0.63, 1.65, 2.15, and 3.75-μm bands by employing an adding-doubling radiative transfer routine (Chang and Li 2002). The radiative transfer calculations were conducted for various sets of cloud optical depths and with different slopes of linear DER vertical profiles. The DER (r_e) within the cloud column is assumed to be a linear function of the in-cloud optical depth (τ') from cloud top ($\tau' = 0$) to cloud bottom ($\tau' = \tau$), which is defined by

$$r_e(\tau') = r_{e1} + (r_{e2} - r_{e1})\frac{\tau'}{\tau_{total}}, \tag{1}$$

where τ_{total} is the total-column cloud optical depth and r_{e1} and r_{e2} are two ideal boundary DERs at cloud top ($\tau' = 0$) and cloud bottom ($\tau' = \tau$), respectively. The DER is given by (Hansen and Travis 1974)

$$r_e = \frac{\int \pi r^3 n(r)dr}{\int \pi r^2 n(r)dr}, \tag{2}$$

and a lognormal size distribution is used for n(r).

Using such a linear DER profile, infinitesimal cloud layers with varying DER were superimposed in the adding-doubling radiative transfer calculations. For fast radiative transfer calculations, the adding-doubling calculations adopted very thin optical depth layers near the cloud top and then adopted progressively thicker layers towards the cloud bottom, as described in Chang and Li (2002). Figure 1 shows the simulated NIR reflectances at 1.65 and 3.75 μm, which were calculated for a cloud layer of $\tau_{total} = 20$ using various values of r_{e1} and r_{e2} for different linear DER profiles. It is seen that the NIR reflectances depend on both the cloud-top r_{e1} and the linear variance defined by $r_{e2} - r_{e1}$. Since the larger the DER the more the absorption, the reflectance dependence on r_{e2} decreases as r_{e1} increases. Also, since the longer wavelength the more absorption by the same droplet size; 3.75-μm reflectance is much less sensitive to variations in r_{e2}, as opposed to the 1.65-μm reflectance. Thus, an independent DER retrieval inferred from the 1.65-μm channel would convey the DER information at a deeper cloud layer than the retrieval from the 3.75-μm channel. Such reflectance dependence on both r_{e1} and r_{e2} lays the foundation for retrieving a linear DER profile.

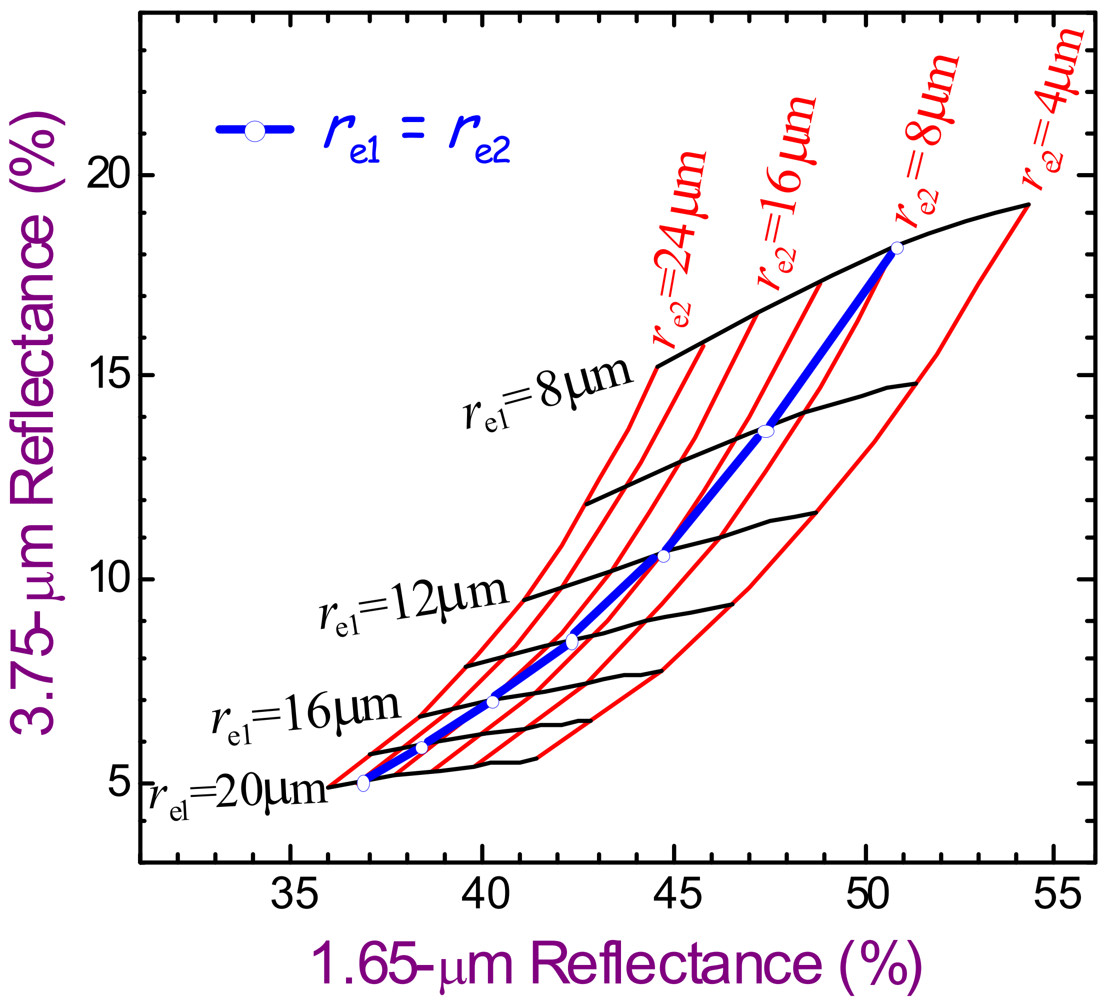

Figure 1. Theoretical NIR reflectances calculated at 1.65 and 3.75 μm for various r_{e1} - r_{e2} linear DER variations with τ_{total} = 20.

Retrieval Procedure

The proposed linear-DER retrieval method starts with a procedure similar to the conventional one by following an iterative procedure to retrieve cloud optical depth and DER from the 0.63-μm measurement and a NIR measurement, for example, at either 1.65 or 3.75 μm. During this retrieval procedure, the DER profile was assumed to be constant with no vertical variations (i.e., the difference $r_{e2} - r_{e1} = \Delta r_e = 0$). However, for cloud DER having inhomogeneous vertical variations, the retrieved DER obtained using the 1.65-μm measurement will differ from that obtained using the 3.75-μm measurement due to different photon penetration depths. The difference between the two DER retrievals from 1.65 and 3.75 μm can thus be used to determine the slope (Δr_e) of the linear DER profile. The DER retrieval is then improved by replacing the constant DER profile with the new $r_{e1} - r_{e2}$ linear DER profile.

Figure 2 illustrates the procedure of the linear DER retrieval using the 1.65 and 3.75-μm measurements. In Figure 2a, the conventional DER retrievals are illustrated by assuming a constant DER vertical profile. For the case where DER increases monotonically from cloud base to cloud top, the retrievals rendered $r_e = 13.1$ μm by using 3.75-μm and $r_e = 11.7$ μm by using 1.65-μm channel. In Figure 2b, using a linear DER profile with a fixed slope of $\Delta r_e = 13.1–11.7$ μm = 1.4 μm, the resulting retrievals rendered $r_{e1} = 13.1$ μm and $r_{e2} = 11.6$ μm using 3.75-μm and $r_{e1} = 12.1$ μm and $r_{e2} = 10.7$ μm using the 1.65-μm channel. With increasing Δr_e for a larger slope of r_e profile, the two retrieved linear DER profiles matched more closely to each other by capturing the trend of the DER vertical variations as shown in Figure 2c. Such a bi-spectral approach can be applied to the multi-spectral NIR measurements, such as 1.65, 2.15, 3.75 μm, to obtain an averaged linear DER profile.

Comparisons with Ground-Based Radar Measurements

The linear-DER retrieval method was applied to the MODIS satellite observations overpass at the ARM SGP CF site (36°37'N and 97°30'W). The ground-based retrievals of the cloud DER vertical profiles were derived using radar reflectivity measurements from cloud profiling radar deployed at the SGP site (Dong and Mace 2002). The radar retrieval method utilizes reflectivity profile measured by millimeter radar together with liquid water path derived from microwave radiometer measurements, from which the vertical profiles of cloud LWC and DER were retrieved. Two different retrieval algorithms of Frisch et al. (1995) and Dong and Mace (2002) were employed and compared with the satellite-based retrievals from MODIS. Two stratus cloud cases were identified at ARM SGP site on April 4 and May 31, 2001, for the MODIS satellite passing time. For ground retrievals, the retrieved DER profiles were averaged over a 15-minute period at around the MODIS passing time. For satellite retrievals, however, the retrieved DER profiles were averaged over an area of $(15\ \text{km})^2$ center at the SGP site. The spatial and temporal sampling of the data contributed certain uncertainty in the comparisons.

Figure 3 compares the satellite-deduced DER vertical profiles with the ground-based radar measurements for the two-stratus cloud retrievals obtained on April 4 (Figure 3a) and May 31 (Figure 3b). In general, the mean cloud DER on May 31 increased with height from cloud base to cloud top; but it decreased on April 4. Both ground radar retrievals exhibited similar trends in terms of increase or decrease, but the DER retrievals from Dong and Mace's algorithm (blue) are on average larger than

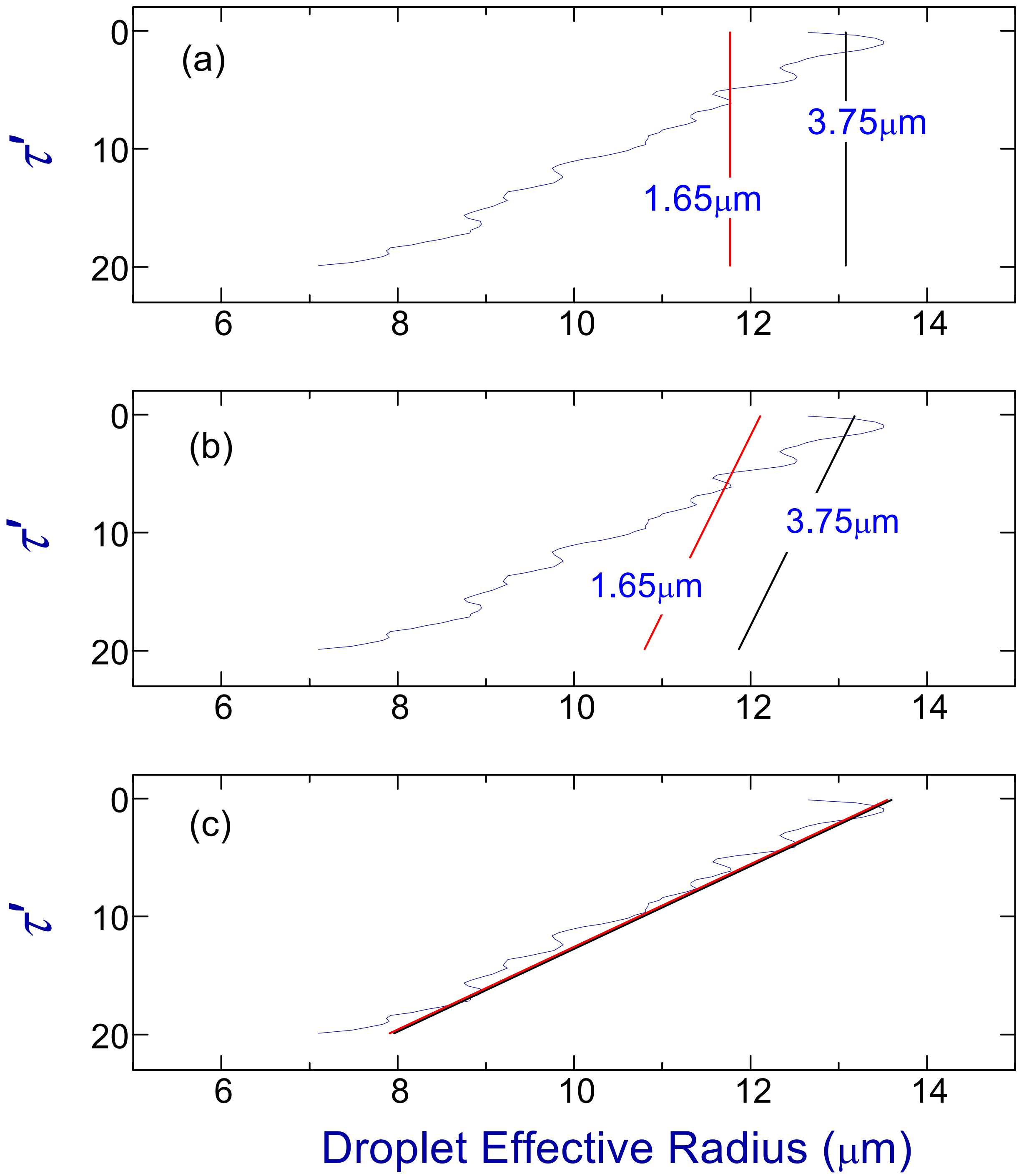

Figure 2. Schematic illustration of the linear DER retrieval procedures from (a) to (c), using 3.75- and 1.65-μm measurements to determine an optimal linear DER profile.

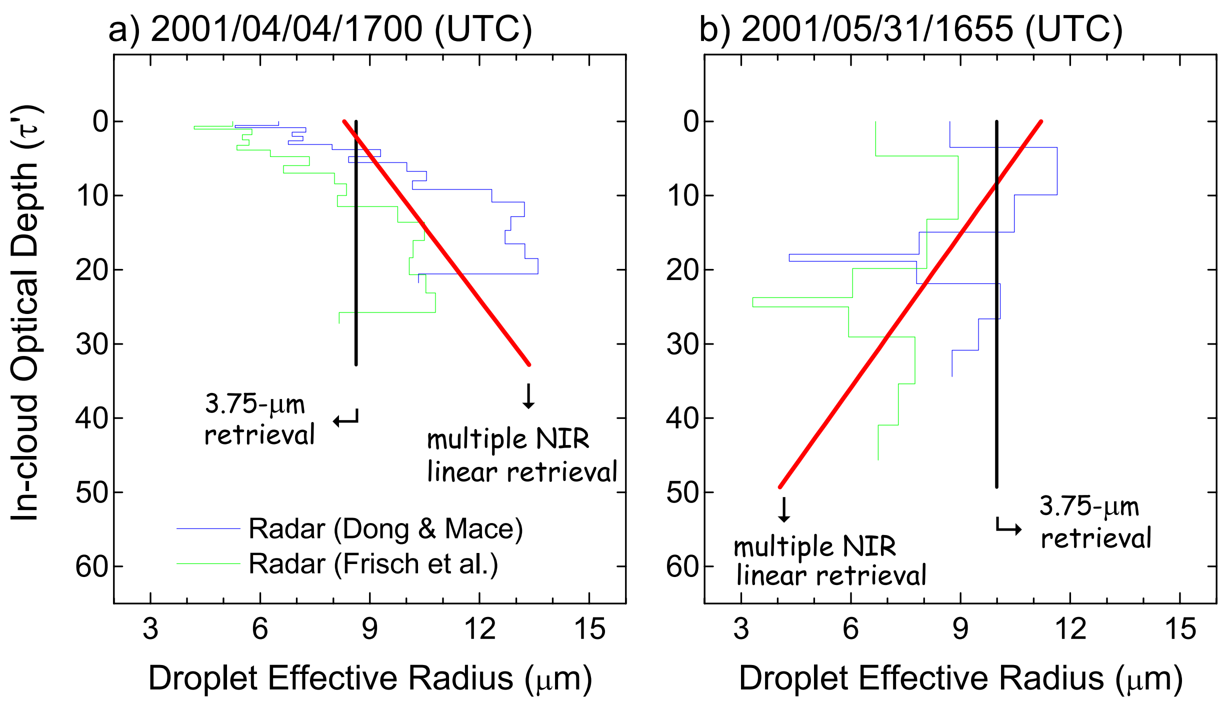

Figure 3. Comparisons of the DER vertical profiles retrieved from MODIS satellite observations (red and black) and ground-based radar measurements (blue and green) over the ARM SGP site.

those from Frisch et al. (1995) (green) by about 2 μm. For satellite-based retrievals, Figure 3 also shows the comparisons of the linear DER profiles that were retrieved by utilizing MODIS 3.75, 2.15, and 1.65-μm multi-channel measurements (red) and the conventional constant DER profiles that were retrieved using only a single 3.75-μm channel (black). Apparently, the DER retrievals using a single NIR channel were inadequate to represent the DER variation for a vertically inhomogeneous cloud layer. As the 3.75-μm reflectance is mainly affected by cloud top, its retrieval is closer to the cloud-top DER values and thus prone to systematic biases towards cloud bottom. On the other hand, using multiple NIR channels the retrieved linear DER profiles display the capability of capturing the trend of DER variations from cloud top to cloud base. The comparisons demonstrate both the necessity and applicability of using multi-spectral NIR measurements to retrieve the DER vertical variations as low-level cloud DER often varies monotonically with height.

Future Work

For future work, we will conduct an extensive validation study to evaluate the performance of the linear DER retrievals using multi-spectral NIR measurements from MODIS satellite observations. The validation requires the use of ARM cloud microphysical measurements derived in lieu of in situ observations and ground-based remote sensing. The ground-based DER retrievals will utilize the radar reflectivity profile together with microwave liquid water path measurements. The University of North Dakota Citation aircraft also provided in situ measurements of cloud microphysics during the ARM cloud intensive observing period at the SGP site for validating the retrievals from remote sensing. Since surface- and aircraft-based measurements only provide samples directly over the site, the complimentary satellite retrievals of cloud properties are important to obtain large-scale and areal mean observations. Satellite retrievals of cloud DER profiles may then be used to better quantify the microphysical properties in boundary layer clouds in order to improve the cloud parameterization schemes required by climate studies.

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